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Effect of improved subgrid scale transport of tracers on uptake of bomb radiocarbon in the GFDL ocean general circulation model

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Abstract. We show that the Gent-McWilliams tracer transport parameterization greatly improves the ability of the GFDL ocean general circulation model to simulate vertical profiles of both temperature and bomb radiocarbon with a single set of model parameter values. This parameterization, which includes new advection terms as well as isopycnal mixing, has previously been shown to greatly improve simulated temperature fields. Here, we show that it does not markedly affect the already good simulation of oceanic absorption of bomb radiocarbon, and discuss the reasons for this result.

Introduction

To make credible predictions of future climate, a model of the ocean circulation must be able to adequately represent the present state of the ocean and the oceanic uptake of anthropogenic CO_2, the most important greenhouse gas. Because it is impossible to observationally distinguish anthropogenic from natural CO_2 in the oceans, model simulations of the oceanic uptake of anthropogenic CO_2 from the atmosphere cannot be tested observationally. For this reason, the ability to simulate the uptake and transport of ^{14}C from atmospheric nuclear bomb tests is often used as an indicator of an ocean model's ability to simulate the uptake of anthropogenic CO_2. The two problems are similar in that they involve the same gas exchange process at the ocean-atmosphere interface, the same transport processes within the ocean, and roughly the same time scales. Oceanic bomb radiocarbon concentrations, however, can be inferred with reasonable accuracy from the GEOSECS and other observations (Broecker et al., 1994).

The global ocean models most widely used in climate studies have been the GFDL model (Pacanowski et al., 1991) – originally developed by Bryan (1969, 1979) – and its relatives (Semtner and Chervin 1988). As usually configured, this model poorly simulates the vertical profile of temperature. Horizontal mean model temperatures are about right near the surface and in the deep ocean, but are up to about 4 degrees too warm at depths of 1 to 2 km (Hirst and Cai 1994, Duffy et al. 1994). This problem is due to the use of horizontal rather than isopycnal diffusion to represent the mixing effects of sub-grid scale eddies (Hirst and Cai 1994, Jain et al. 1994). Mixing in the real ocean occurs almost exclusively along isopycnal (constant density) surfaces, and these surfaces slope steeply enough at high latitudes that vertical mixing in these regions is dominated by the vertical component of isopycnal mixing. Thus, intermediate depth waters are cooled by isopycnal mixing with surface waters at high latitudes (Hirst and Cai 1994). Models with horizontal (as opposed to isopycnal) mixing have insufficient mixing between intermediate depths and cold high latitude surface waters and as a result are too warm at depths of 1 - 2 km.

The representation of the thermocline could be improved by reducing the model's vertical sub-grid scale mixing, but then simulated uptake of transient tracers like bomb ^{14}C and anthropogenic CO_2 would be inadequate. It has been impossible with the GFDL model using horizontal/vertical mixing to properly simulate the vertical temperature profile and the uptake of transient tracers at the same time (Toggweiler at al. 1989; Duffy et al. 1994). Vertical diffusivities which are too low to get the simulated bomb radiocarbon uptake right are at the same time too high to get the model thermocline right. The same problem has also been seen in one-dimensional ocean models (Seigenthaler and Joos, 1992; Jain et al. 1994).

At least two recent studies have shown that the GFDL model's representation of the vertical temperature structure of the ocean is improved by using isopycnal mixing of tracers to represent the effects of subgrid scale eddies. Hirst and Cai (1994) did so using the isopycnal mixing scheme of Cox (1987). Danabasoglu et al. (1994) used the Gent and McWilliams (1990; hereafter GM90) parameterization of subgrid scale eddies, which includes isopycnal mixing of tracers as well as new advective terms representing eddy-induced transport velocities. In this paper, we show that the improvement in the vertical temperature structure brought about by the GM90 parameterization is obtained without significantly worsening the simulated uptake of transient tracers; i.e., that the GM90 parameterization improves the GFDL model's ability to simulate vertical profiles of temperature and a transient tracer (bomb ^{14}C) with one set of parameter values. The effects of the GM90 parameterization on the model's dynamical fields are discussed by Danabasoglu et al. (1994), Boning et al. (1994), and Danabasoglu and McWilliams (1994); this paper therefore focuses on how the GM90 parameterization affects the GFDL model's uptake and transport of bomb ^{14}C.

Results and Discussion

We discuss two different simulations with the GFDL ocean model of the uptake and transport of bomb ^{14}C. The first is that of Duffy et al. (1994) which uses Laplacian horizontal and

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vertical subgrid scale mixing of tracers, with spatially uniform mixing coefficients of $2x10^7$ cm^2/s (horizontal) and 0.2 cm^2/s (vertical). This will be referred to as HOR. The second simulation (ISO) is identical to the first except that the horizontal/vertical Laplacian sub-grid scale mixing of tracers is replaced by the isopycnal diffusion/advection eddy parameterization of Gent and McWilliams (1990). Mixing coefficients here are 0.2 cm^2/s (vertical) and $1x10^7$ cm^2/s (isopycnal).

Both simulations use the version of the GFDL model described by Duffy et al. (1994). The main difference between this and the publicly distributed version is that we have coupled the ocean model to the dynamic/thermodynamic sea ice model of Oberhuber (1993). In addition, we use Oberhuber's surface boundary condition for heat, in which longwave, shortwave, latent, and sensible fluxes of heat are calculated from monthly observed atmospheric data. Surface salinities are restored to monthly mean observed values (Levitus, 1982) and wind stresses are prescribed, based on monthly average observed winds (Hellerman and Rosenstein, 1983). Tropospheric concentrations of bomb ^{14}C are prescribed, and air-sea gas exchange is parameterized, using the same wind speed dependent formulation as Duffy et al. (1994). The model was run with a horizontal grid size of 3 deg. latitude by 3 deg. longitude, with 15 vertical levels. Subgrid scale mixing of momentum is the same in the two runs, and is parameterized by horizontal/vertical Laplacian diffusion with spatially uniform mixing coefficients of $1x10^9$ cm^2/s (horizontal) and 20 cm^2/s (vertical). Before bomb radiocarbon was introduced, the both configurations of the model were run for 600 simulated years to bring the temperatures, salinities, and velocities towards a steady state.

In HOR, described above, model temperatures are roughly correct at the surface and in the deep ocean, but are up to about 4 degrees too high at depths of 1 to 2 km (Figure 1). As described above, this is due to the use of horizontal subgrid scale mixing of tracers, which allows insufficient vertical mixing at high latitudes.

The simulation of oceanic uptake of bomb ^{14}C in HOR is reasonably realistic. The mean model surface concentration is about 12% higher than the mean value inferred from the GEOSECS observations by Broecker at al. (1994; Table 1). HOR's mean column inventory (vertical integral) of bomb ^{14}C at the GEOSECS stations is about 10% lower than the value inferred from observations by Broecker at al. (1994) of $9.35 \cdot 10^9$ atoms of ^{14}C per cm^2 (Table 1). These comparisons were made by interpolating the model results to the time and place of each observation, and comparing the mean model result to the mean observed value. (This method is used throughout this paper.) Thus in HOR the total amount of bomb ^{14}C absorbed by the ocean is too low, but the mean surface concentration is too high.

The vertical profile of bomb ^{14}C is usefully characterized by the penetration depth, which Broecker et al. (1985) define as the vertical integral of the bomb ^{14}C concentration (the column inventory) divided by the surface concentration of bomb ^{14}C. As suggested by the model surface concentration being too high and the column inventory being too low, the mean model penetration depth at the 112 GEOSECS stations in HOR is about 11% lower than the mean observed value (Table 1).

Table 1. Bomb-produced ^{14}C surface concentrations (in units of $\Delta^{14}C = 1.528 \cdot 10^3$ atoms/cm^3), column inventories (10^9 atoms/cm^2), and penetration depths (m) as inferred from the GEOSECS observations (GEO) by Broecker et al. (1994), and as simulated by the GFDL general circulation model, both with (ISO) and without (HOR) the Gent-McWilliams eddy transport parameterization. The GEOSECS values are averages at stations in the Atlantic, Pacific, and Indian oceans; model results were interpolated to the time and place of each GEOSECS observation and then averaged.

	GEO	HOR	ISO
Surface concentration ($\Delta^{14}C$)	154.3	172.7	181.1
Column inven. (10^9 atoms/cm^2)	9.35	8.37	8.28
Penetration depth (m)	390.4	348.0	315.9

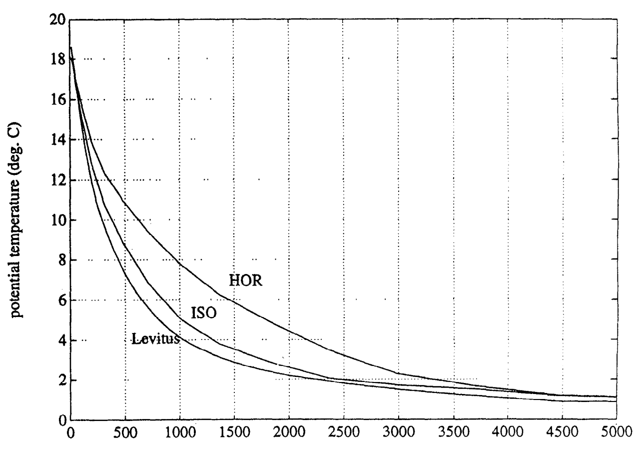

Figure 1. Vertical profiles of global average, annual mean potential temperature in two simulations with the GFDL global ocean general circulation model, and as observed by Levitus (1982).

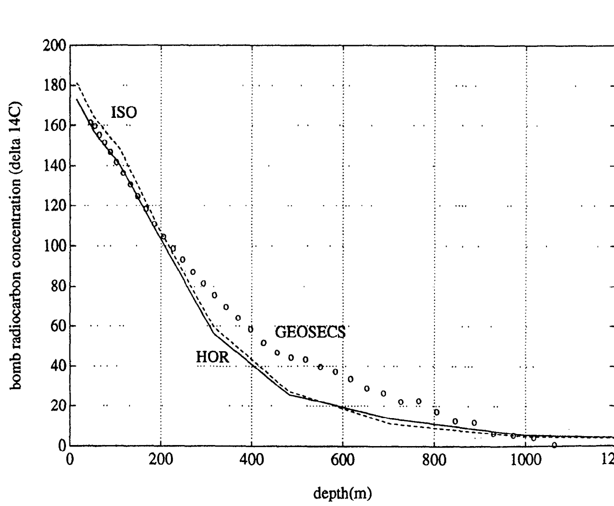

Figure 2. Mean vertical profiles of concentrations bomb ^{14}C at the GEOSECS stations, in two simulations with the GFDL global ocean general circulation model, and in the GEOSECS observations. The solid line is HOR; the dashed line is ISO; the "o"s represent observations.

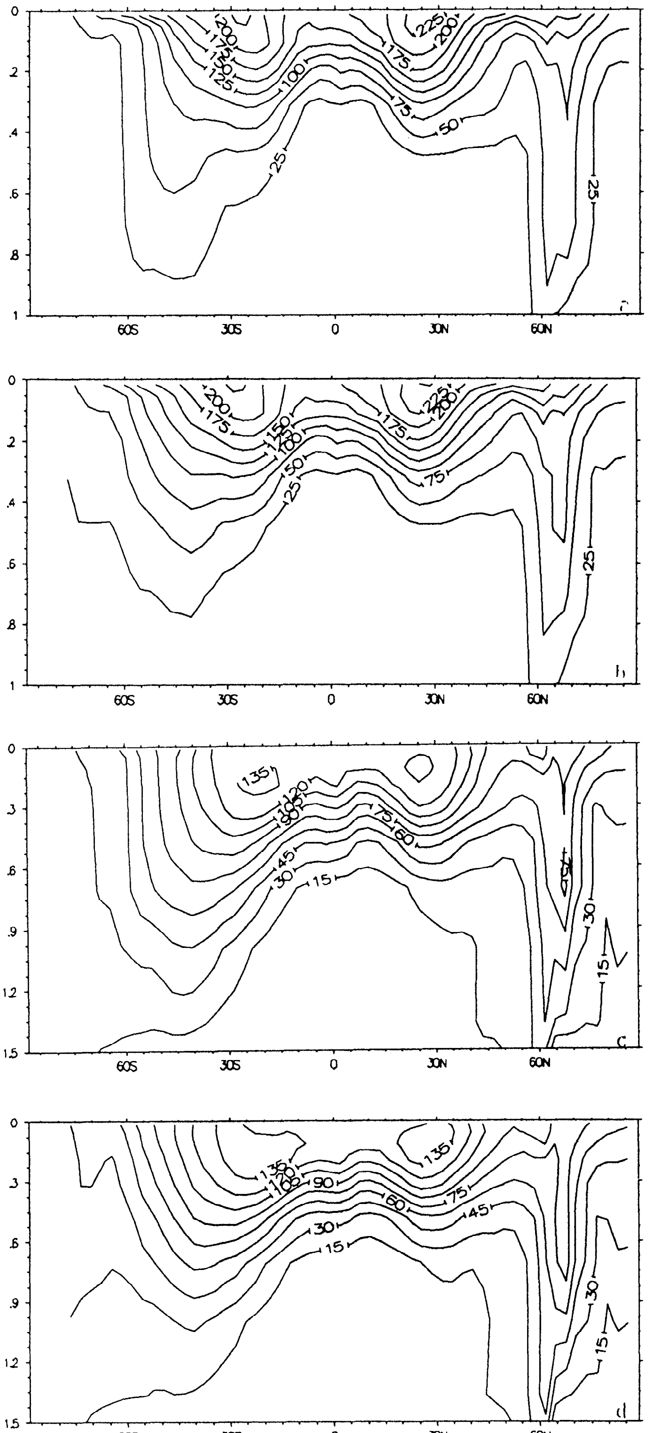

Figure 3. Zonally averaged latitude-depth sections of bomb ^{14}C in 1975 (Panels a and b) and 1995 (Panels c and d) as simulated in the GFDL model. Panels a and c (HOR) are with horizontal Laplacian diffusion for sub grid scale mixing of tracers. Panels b and d (ISO) use the Gent and McWilliams (1990) parameterization of tracer transport by eddies.

As mentioned above, our second simulation of bomb ^{14}C replaces the horizontal/vertical Laplacian mixing of tracers used in HOR with the GM90 eddy transport parameterization. The simulations are otherwise identical. As expected from the results of Danabasoglu, McWilliams, and Gent (1994) – who used the GM90 parameterization – and Hirst and Cai (1994), the representation of the thermocline is much better in ISO than in HOR (Figure 1). Danabasoglu, McWilliams, and Gent (1994) present a detailed discussion of the effects of the GM90 parameterization on the temperature structure in the GFDL model. The GM90 parameterization reduces temperatures at intermediate depths despite increasing overall vertical transport because the increased vertical transport occurs only at high latitudes, where surface waters are cold.

What might not be expected is that the vertical profile of bomb ^{14}C appears almost unchanged (Figure 2, Table 1). In addition, latitude-depth sections of bomb ^{14}C as of 1975 (Figure 3a,b) are also nearly identical in the two runs. This relatively small change is the net result of large changes in the individual transport processes (advection, diffusion, and convection) which tend to cancel each other, leaving a small overall change in the vertical profile of bomb ^{14}C. Table 2 shows fluxes of bomb ^{14}C into the sub-surface ocean from the top model layer due to all relevant transport processes, averaged over the year 1971, for ISO and HOR. The GM90 parameterization reduces convective transport by about a factor of 30, consistent with the results of Danabasoglu, McWilliams, and Gent (1994). The GM90 parameterization increases vertical transport by diffusion (by about a factor of 5), because in many locations the vertical component of isopycnal mixing greatly exceeds the prescribed vertical mixing. Advective transport is reduced by the GM90 parameterization, due to the inclusion of additional "isopycnal advection" terms. Despite these large changes in the individual transport components, the total rate of change of the bomb ^{14}C concentration is only slightly less with the GM90 parameterization than without it.

The fact that these changes nearly cancel each other is not entirely coincidental. The reduction in convective transport – which with horizontal mixing occurs mainly at high latitudes (Danabasoglu et al. 1994) – is no doubt due to the replacement of horizontal mixing by isopycnal mixing, which by definition cannot create density instabilities. Thus isopycnal mixing both reduces convective transport and increases vertical diffusive transport, and these effects tend to cancel

Table 2. Bomb ^{14}C fluxes into the subsurface ocean from the surface layer, averaged over the year 1971, as simulated by the GFDL general circulation model, both with (ISO) and without (HOR) the Gent-McWilliams eddy transport parameterization. Downward transport of bomb ^{14}C is defined to be positive. Row 1 is the sum of rows 2, 5 and 6. Row 2 is the sum of rows 3 and 4. In the ISO case, row 5 includes the vertical component of isopycnal diffusion.

Downward bomb ^{14}C flux (10^{18} atoms/s) due to:	HOR	ISO
1 All transport processes	50.46	48.39
2 Total advection	26.78	13.58
3 Non-isopycnal advection	26.78	25.67
4 Isopycnal advection	0	−12.08
5 Diffusion	6.58	34.27
6 Convection	17.11	0.56
Subsurface inventory 1971 (10^{28} atoms)	2.308	2.302

each other. The small change in the bomb ^{14}C distribution between ISO and HOR is also partly due to the fact that at the time of the GEOSECS observations (the mid-1970s) bomb radiocarbon was largely confined to the upper 400 - 500 m of the ocean (Figure 3ab), whereas the biggest changes in the temperature structure occur between 1 km and 2 km depth. At later times the differences between the radiocarbon distributions in HOR and ISO are more distinct (Figure 3cd). This figure also verifies that, as noted above in the discussion of temperature profiles, the increased vertical transport caused by the GM90 parameterization is primarily at high latitudes.

Conclusions

We have shown that the parameterization of the effects of sub grid scale eddies of Gent and McWilliams (1990), which allows the GFDL global ocean general circulation model to realistically simulate the vertical profile of temperature in the ocean, does so without significantly compromising the model's ability to simulate the oceanic uptake of a transient tracer (bomb ^{14}C).

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